

Addressing foundational elements of regional land-use change forecasting

Terry L. Sohl · Thomas R. Loveland · Benjamin M. Sleeter ·
Kristi L. Sayler · Christopher A. Barnes

Received: 27 February 2009 / Accepted: 16 July 2009
© Springer Science+Business Media B.V. 2009

Abstract Regional land-use models must address several foundational elements, including understanding geographic setting, establishing regional land-use histories, modeling process and representing drivers of change, representing local land-use patterns, managing issues of scale and complexity, and development of scenarios. Key difficulties include managing an array of biophysical and socioeconomic processes across multiple spatial and temporal scales, and acquiring and utilizing empirical data to support the analysis of those processes. The Southeastern and Pacific Northwest regions of the United States, two heavily forested regions with significant forest industries, are examined in the context of these foundational elements. Geographic setting fundamentally affects both the primary land cover (forest) in the two regions, and the structure and form of land use (forestry). Land-use histories of the regions can be used to parameterize land-use models, validate model

performance, and explore land-use scenarios. Drivers of change in the two regions are many and varied, with issues of scale and complexity posing significant challenges. Careful scenario development can be used to simplify process-based land-use models, and can improve our ability to address specific research questions. The successful modeling of land-use change in these two areas requires integration of both top-down and bottom-up drivers of change, using scenario frameworks to both guide and simplify the modeling process. Modular approaches, with utilization and integration of existing process models, allow regional land-use modelers the opportunity to better represent primary drivers of land-use change. However, availability of data to represent driving forces remains a primary obstacle.

Keywords Land · Change · Model ·
Regional · Foundation

T. L. Sohl (✉) · T. R. Loveland · K. L. Sayler
US Geological Survey, Earth Resources Observation and
Science (EROS) Center, Sioux Falls, SD 57198, USA
e-mail: sohl@usgs.gov

B. M. Sleeter
US Geological Survey, Western Geographic Science
Center, Menlo Park, CA 94025, USA

C. A. Barnes
SGT Inc., Contractor to US Geological Survey, Earth
Resources Observation and Science (EROS) Center,
Sioux Falls, SD 57198, USA

Introduction

Forecasts of land use and land cover are needed for multiple applications, including those examining effects on water quality, biodiversity, carbon balances, and climate change (Loveland et al. 2003). Increasingly many of these applications require land-use data at regional scales, but at relatively high spatial resolutions that realistically portray landscape pattern. Over the last decade, vast improvements

have been made in data availability, with freely available remote-sensing data providing many key biophysical inputs, while improvements have also been made in the availability and integration of economic and social sciences data (Verburg et al. 2008). Along with increases in computing power, improvements in modeling environmental processes, and new methodologies to represent uncertainty (Pontius and Spencer 2005; Pontius et al. 2008), we have greatly improved our ability to forecast land-use and land-cover change.

However, land-use and land-cover processes are extremely complex. Difficulties remain in trying to simulate global to local scale biophysical processes (e.g., global climate change down to parcel-level changes in biogeochemical structure of the soil), socioeconomic processes and human decision-making (e.g., global commodity prices down to individual land-owner decisions on agricultural land management), and feedbacks between biophysical and social processes. Parker et al. (2002) state that if modelers are to provide modeling tools for policy makers, they need to move away from abstract, generative models of land-use change to more realistic, descriptive models based on real-world data and processes. There has been a tendency for some land-use modeling efforts to focus on either environmental or socioeconomic processes (Irwin and Geoghegan 2001), although land-use change itself typically occurs as a result of interactions between both of these processes. In the last decade land-use modeling efforts, using probabilistic modeling based on empirically derived relationships between land-use and land-use drivers, have attempted to capture interactions and feedbacks between the biophysical and socioeconomic environments (Brown et al. 2002; Verburg and Veldkamp 2004; Verburg et al. 2004), while other models have incorporated empirically derived data on environmental processes into analysis of the human decision-making process (Parker et al. 2002, 2004). There are many modeling efforts that are now attempting to model human-environment interactions at multiple scales, feedbacks among drivers, and the resultant impacts on land-use change. As these modeling efforts increase in complexity, obvious gaps appear in our understanding of land-use processes and in the availability of data which allow modelers to explore these processes.

For regional land-use modeling, there are a suite of “foundational elements” which typically need to be addressed. This paper discusses several of the foundational elements of regional land-use modeling, and how those elements would potentially affect land-use modeling efforts for two geographic regions, the Southeastern US and Pacific Northwest. The discussion touches on gaps in basic data availability, our understanding of land-use change processes and ability to model them, and the challenges unique to each of the two regions. Note the discussion focuses primarily on land-use and land-cover modeling (discrete thematic land-use and/or land-cover classes), although many factors are fundamental for all forms of land-change modeling.

Foundational elements for regional land-use forecasting

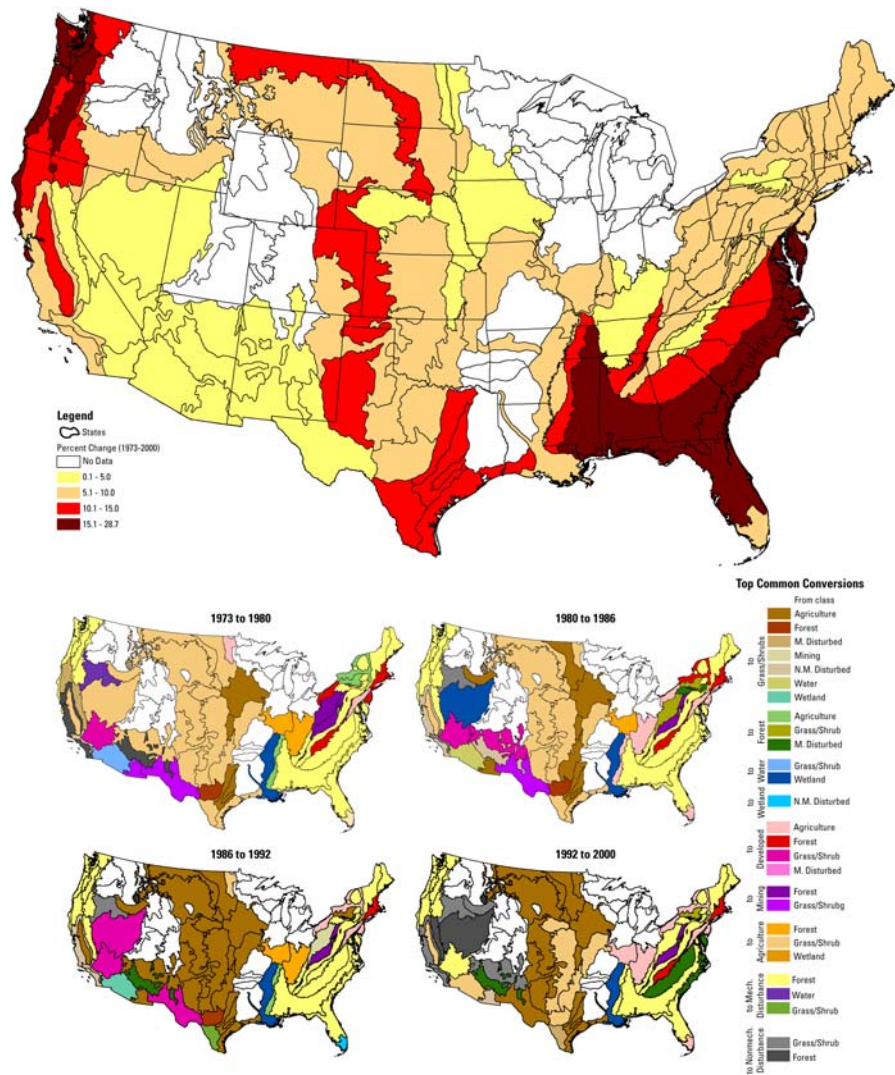
Project design and methodology for land-use forecasts are directly related to the required use of the forecast data. Ultimately, the required thematic, spatial, and temporal resolution of land-use forecasts depends upon how model outputs will be utilized. These design characteristics are what drive model technique and required inputs.

However, for regional landscape modeling, there are a suite of factors which typically need to be explicitly addressed. This non-exclusive list includes the following.

Understanding of geographic setting

The one commonality linking all components of a land-use forecast model is the emphasis on geographic location (Rindfuss et al. 2004). Ecological and socioeconomic processes driving land-use change are unique for a given geographic region, as are the resultant spatial patterns of land-use change (Loveland et al. 2002; Gallant et al. 2004; Sohl and Saylor 2008; Verburg et al. 2008; Fig. 1). Land owners and resource managers adapt to driving forces within the constraints or opportunities associated with geographic and ecological setting, including the influence of settlement history. The unique drivers and spatial characteristics of change must be understood within a geographic or ecologic region. As a

Fig. 1 Common land cover conversions for ecoregions of the conterminous United States (Omernik 1987), as measured by the USGS Land Cover Trends project (Loveland et al. 2002). Primary land cover conversions vary both geographically and temporally, with each ecoregion characterized by unique rates, spatial patterns, and temporal patterns of change



result, it is evident no single approach to land-use forecasting can be applied to all regions.

Establishment of regional land-use history

Land-use histories are valuable for regional scenario development (Brown et al. 2002; Marcucci 2000), for speculative problem-solving (Tomlin 1990), or for calibrating and validating model performance (Wu et al. 2008). Land-use models often rely on spatially explicit land-use histories for parameterization and training, using historical characteristics to inform future projections (Claggett et al. 2004; Sohl et al. 2007; Sohl and Saylor 2008). Regional land-use histories, in conjunction with well-documented histories of major

drivers of change, are invaluable for establishing cause and effect (i.e., how a given region responds to changes in driving forces). Given the importance of geographic setting, consistent land-use histories are an invaluable resource for any regional land-use forecast project.

Modeling process and representing drivers of change

The biophysical and socioeconomic drivers of land-use change vary spatially and temporally. As a result, deterministic models based on land-use history alone cannot adequately portray the variety of potential landscapes that may occur. There is a need to

establish a connection between social science and spatial land-use models (Geoghegan et al. 1998; Rindfuss et al. 2004; Matthews et al. 2007). Land-use and land-cover forecast models must endeavor to establish causality, linking human decision-making with environmental and socioeconomic drivers at all representative scales of analysis. A key difficulty in establishing those linkages is the acquisition of spatial data representative of key drivers of change (Parker et al. 2002; Sohl et al. 2007).

Representation of local land-use pattern

There are clear spatial dimensions to land-use change (Fig. 2), and those patterns depend on both physical (e.g., topographic expression) and cultural (e.g., land

tenure) factors (Gallant et al. 2004). Local land-use pattern has a strong influence on biodiversity, species persistence, and ecological function (Poudevigne and Baudry 2003; Wimberly and Ohmann 2004), as well as water quality (Zampella et al. 2007), making proper representation of local land-use pattern a key requirement for evaluating the consequences of land-use change (Brown et al. 2002). Improvements are required for modeling spatial patterns of land-use change (Wu et al. 2008). A key difficulty is establishing linkages between social and biophysical drivers of change and changes in land-use patterns (Verburg 2006). An understanding of such linkages would allow for more robust modeling of future land-use pattern in response to future changes in driving forces.

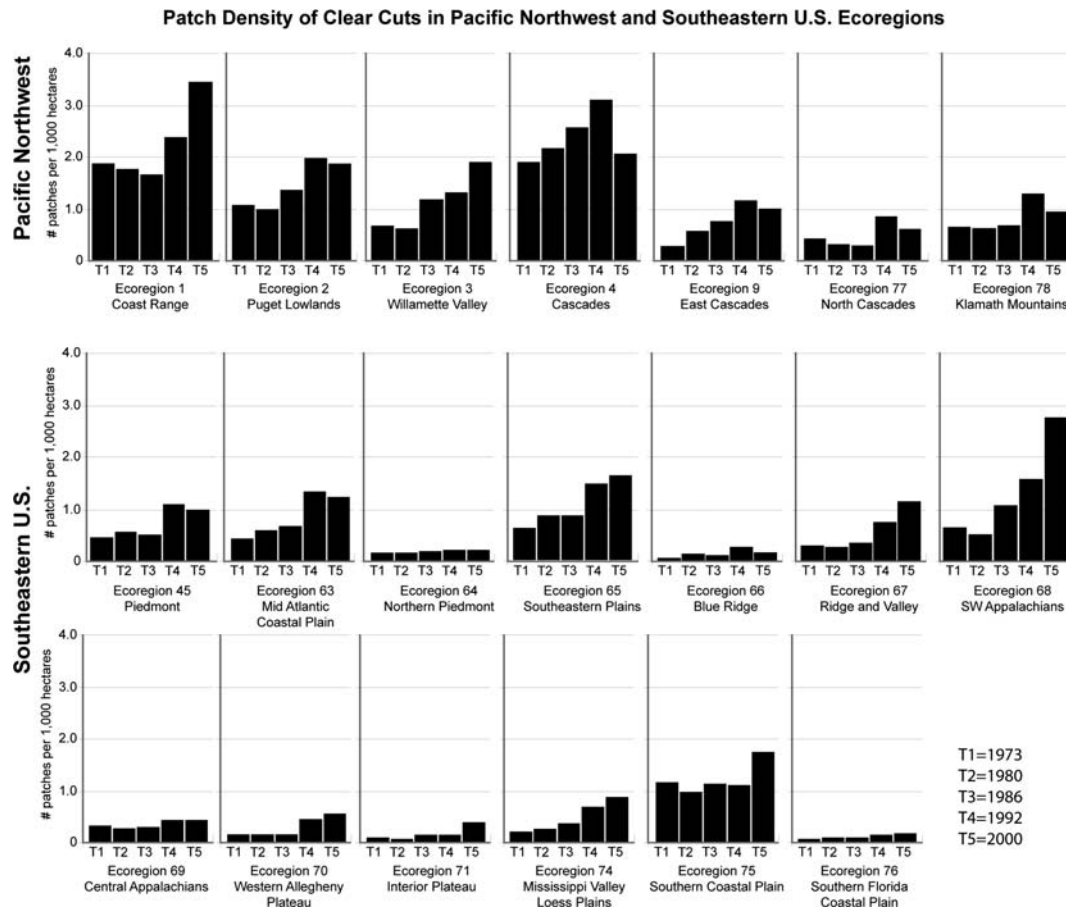


Fig. 2 Spatial and temporal characteristics in patch density of clear-cuts among different ecoregions of the southeastern US and Pacific Northwest. Spatial dimensions of landscape change

are unique to each region and must be properly represented for regional land-use forecasts

Managing issues of scale and complexity

Most land-use models do not account for the full range of scales affecting change (Verburg et al. 2008; Naveh 2001). Landscape processes have inherent scales, and any attempt to model those processes at different or aggregated scales will inevitably fail (Parker et al. 2002). Some of the difficulty lies with data availability. For example, Claggett et al. (2004) noted the difficulty in properly simulating local development pressure because accurate data on land value and landowner characteristics were sporadically available. Even when sufficient data exists, modelers face the challenge of integrating their analyses across multiple spatial and temporal scales. A vast array of diverse drivers affect land-use change, and attempting to account for all of them while maintaining a manageable level of model complexity remains a challenge.

Need for scenario development

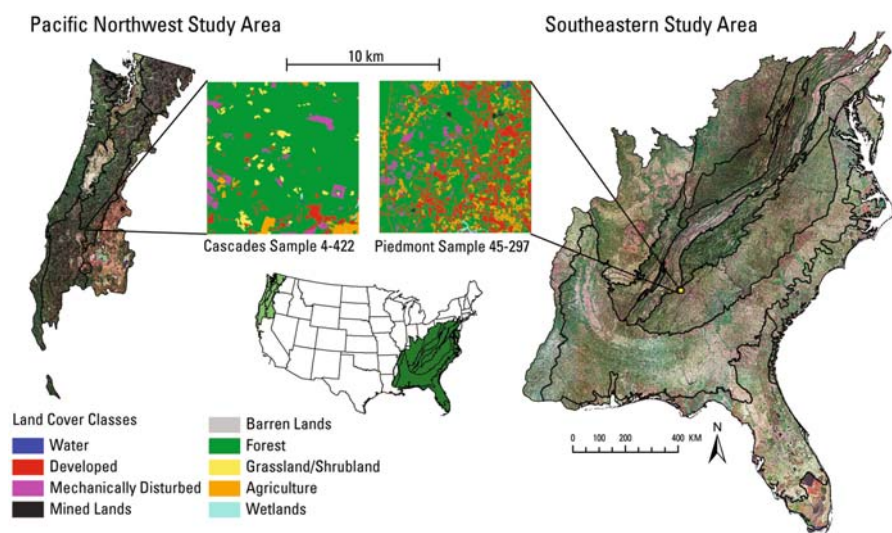
The goal of land-use forecasting is not to deterministically predict the future, but to represent possible outcomes under specific scenarios. Prediction implies that pre-defined conditions established in a forecast model will continue to hold into the future (Parker et al. 2002). Land-use modeling should focus on anticipation of the possible and a prescription for the desired (Naveh 2001). The development and implementation of multiple scenarios in a land-use model

allows for an exploration of the processes affecting land-use change. Scenarios show what potentially could happen in the future as a result of policy or environmental change, and thus help decision-makers mitigate potentially negative consequences of their actions.

Foundational elements: southeastern US and the Pacific Northwest

Here we examine each of the foundational elements of regional land-use modeling discussed above in the context of theoretical modeling efforts in two unique geographic regions in the United States. The southeastern US and the Pacific Northwest (Fig. 3) are both characterized by a strong forestry influence, with national to global influences on wood product markets. The two regions are both characterized by favorable biophysical settings for the production, management, and utilization of forest resources. Forecasts of land-use in the two regions are needed for exploration of many issues. Despite many similarities in land cover and land use in the two regions, the driving forces affecting forest cover and use, as well as other forms of change, are quite different, leading to different requirements for successfully modeling change. The examples below are used to highlight some of the major challenges affecting regional land-use modeling in the context of these foundational elements.

Fig. 3 The Pacific Northwest and southeastern US study areas. Locations of the USGS Land Cover Trends samples shown in Figs. 7 and 9 are also depicted



Understanding geographic setting: southeastern US and Pacific Northwest

Geographic setting sets the potential for land-use and land-cover change in the southeastern US and Pacific Northwest. The climate of the southeastern US is ideally suited to agriforestry. Pine plantations have emerged as a significant land use, making up as much as 50% of forested lands (Conner and Hartsell 2002). Agriculture has historically played an important role in the region, but the latest trend, influenced by both Federal conservation programs and private enterprise, has been the reforestation of agricultural lands to pine plantations. Given the extremely favorable biophysical setting for forest cover, cutting intervals in the southeastern US are short, with a typical rotation of 20–25 years. The result is an ever-changing forest structure which is expected to continue to change due to pressure from regional development and continued strong demand for wood products (Wear and Greis 2002).

While much of the southeastern US forests are associated with broad alluvial plains, Pacific Northwest forests are generally associated with a rugged, mountainous terrain. Biophysical conditions and commercial softwood species in the Pacific Northwest result in longer cutting cycles than in the southeastern US, typically 40 years or more. Agriculture in the region is generally confined to coastal areas and mountain valleys, and thus has had only a minimal influence on recent forest change. Aside from the densely developed regions around Puget Sound and Portland, Oregon, there is little demand on the forested landscape for urban and developed uses.

Biophysical conditions in both ecoregions favor forested land cover, but geographic setting also strongly affects land use and the forest industry in the two regions. One of the most influential trade flows in wood products in the world started after the Columbus Day storms of 1962 blew down billions of board feet of timber in the Pacific Northwest, resulting in salvaged timber flooding world markets (Lane 1998; Daniels 2005). Asian Pacific Rim nations' demand for softwood logs at the time initiated heavy imports of Pacific Northwest logs. Geographic location, availability of deep-water ports, and the biophysical potential to support a forest industry allowed the Pacific Northwest to easily respond to Pacific Rim market demand for timber products. The southeastern

US timber industry is better positioned to supply timber products for domestic use, especially for strong eastern US construction markets. Differences in geographic setting and biophysical conditions fundamentally affect structure and form of the forest industry in the two regions, in terms of species grown, types of timber products supplied, growth rates and resultant cutting cycles, and access to domestic and international markets.

Establishment of regional land-use history: southeastern US and Pacific Northwest

Land-use histories of the two study areas can be used for scenario development, exploration of past response to land-use drivers, model calibration and validation, and model parameterization. However, consistent local land-use histories are often not available for regional land-use forecast applications. In the conterminous US, the US Geological Survey (USGS) Land Cover Trends study provides contemporary (1973–2000) regional land-cover and land-use histories on an ecoregion-by-ecoregion basis (Love-land et al. 2002), data that have proven invaluable for past regional land-use forecasts, (Sohl et al. 2007; Sohl and Sayler 2008).

Land-use histories for the southeastern US and Pacific Northwest offer important clues to regional response to drivers of change. Figure 4 depicts measured rates of forest cutting for 1973–2000 in the

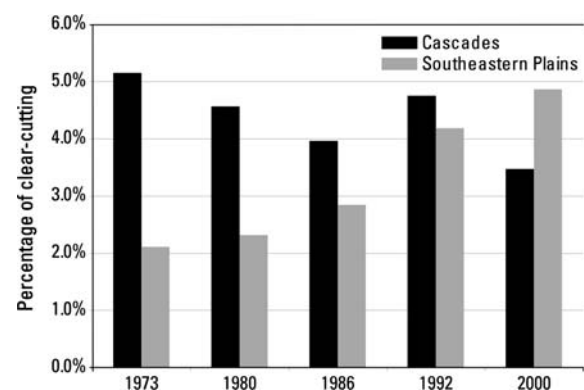


Fig. 4 USGS land cover trends mapped rates of clear-cutting class for the Cascades ecoregion (in the Pacific Northwest) and the Southeastern Plains ecoregion (in the southeastern US), as a percentage of ecoregion area. While rates of cutting have generally declined since 1973 in the Cascades, they have showed steady continuous increases in the Southeastern Plains

Southeastern Plains ecoregion of the southeastern US and the Cascades ecoregion in the Pacific Northwest, showing a general increase in cutting in the Southeastern Plains and a decline in the Cascades ecoregion. Reasons for these patterns include changes in both policy and global economics (as discussed in later sections). Land-use histories such as these, in conjunction with well-documented historical changes in driving force variables, can be used in the establishment of cause and effect (i.e., how a given region responds to changes in driving force variables).

Regional land-use histories can also be used to characterize and model land-use configuration. Figure 2 depicts variations in patch density for forest clear-cut patches in ecoregions of the southeastern US and Pacific Northwest, with individual ecoregions exhibiting unique temporal and spatial characteristics of clear-cutting. Such data on historical landscape metrics for specific land-use transitions have been successfully used to parameterize forecast models. Sohl and Sayler (2008) used ecoregion-specific land-use histories from the USGS trends study to spatially model patterns of land-use change for the southeastern US.

Land-use histories also offer the capability to calibrate and validate model performance. This is often done through the explicit modeling of historical periods to examine model performance relative to empirically measured land-use histories. Sohl and Sayler (2008) compared 1992–2000 forecast model results with patterns of land-use change as measured by the USGS Land Cover Trends project to examine FORE-SCE model performance in the southeastern US. Land-use histories can also be used in the exploration and development of scenarios, through either basic extrapolations of historical land-use patterns (Sohl et al. 2007; Sohl and Sayler 2008), or through the exploration of historical response to specific driving force changes. Land-use histories offer tremendous utility for parameterizing land-use models, improving and validating model performance, and exploring and developing land-use scenarios.

Modeling process and representing drivers of change: southeastern US and Pacific Northwest

An understanding of geographic setting and availability of consistent land-use histories allows for the

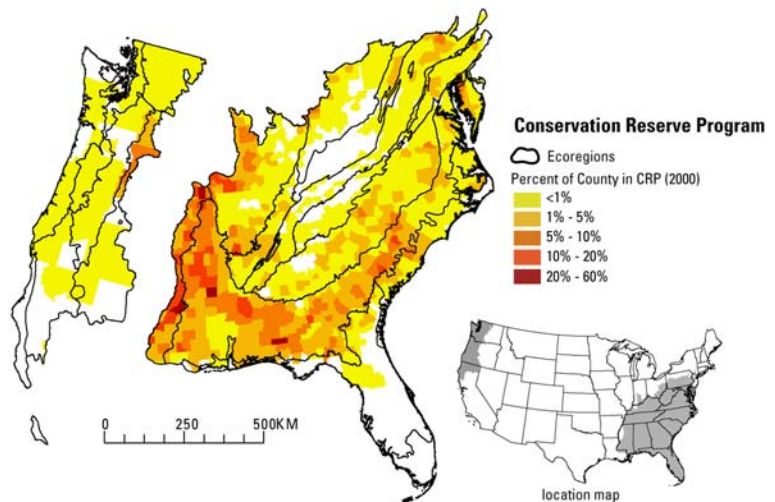
analysis of land-use change processes. Drivers of change operate at global to local scales. This section primarily focuses on global and national drivers of change, drivers which have uniquely affected the southeastern US and the Pacific Northwest.

In the Pacific Northwest, government policies have had significant influences on forestry. US Fish and Wildlife's decision to list the Northern Spotted Owl as "threatened" in 1990 led to the establishment of the Northwest Forest Plan in 1993, a plan which changed much of the focus of forestry on federal lands in the region to preservation of habitat. Logging on national forest lands in the Pacific Northwest declined sharply from the high 1980s levels (Daniels 2005), leading to overall declines in timber harvest and higher percentages of harvest coming from private lands. Pacific Northwest ecoregions with significant public forest land (Ecoregions 4, 9, 77, and 78) showed declines in patch density of clear-cuts between 1992 and 2000, while ecoregions dominated by private forest land (Ecoregions 1, 2, and 3) exhibited increases (Fig. 2). Also during this time, an increase in Canadian exports to the US led to establishment of the Canadian Softwood Lumber Agreement (SLA) of 1996, meant to limit Canadian softwood exports to the US.

These and other policies also had strong, indirect effects on the forest industry in the southeastern US. The strong economy and resulting construction boom in the US in the 1990s brought increased demand for wood products. Southeastern US forestry largely filled the void caused by 1990s declines in Pacific Northwest forestry and limits placed on Canadian imports by the 1996 SLA (Fig. 4). The establishment of the Conservation Reserve Program (CRP) in the mid 1980s also had a strong impact on southeastern US forestry and land use, as over 1,000,000 ha of plantation forestry was planted on marginal agricultural lands. The CRP program, while locally important in a few parts of the Pacific Northwest, had very little effect on that region's forestry (Fig. 5). The potential effects of government policy are uneven, but even more importantly, they are unpredictable and difficult to model, both from the standpoint of predicting what future policy will be, and how those policies will affect land use at a regional scale.

Changes in international trade of wood products have had substantial impacts on the two regions in recent decades. Up until the early 1990s, the United

Fig. 5 Conservation Reserve Program (CRP) impacts on land use in the Pacific Northwest and southeastern US. While significant conversion of marginal agricultural land to pine plantations occurred in the southeastern US, very little conversion occurred in the Pacific Northwest



States was one of the world's lowest cost producers of timber products (Haynes 2003). Nearly all US exports to the Pacific Rim originated in the Pacific Northwest, leading to very high (and eventually unsustainable) rates of cutting in the region by the 1980s. However, starting around 1990, US exports to Pacific Rim markets began to decline, as the Asian economic collapse of the mid-1990s resulted in much lower demand for wood products. Globalization of the wood product industry has also had a negative influence on Pacific Northwest forestry, with Chile, New Zealand, and Russia becoming major forces on the global market. The southeastern US, on the other hand, was traditionally more of a domestic supplier of timber products, and direct effects of the Asian economic collapse or globalization of the wood product industry were small in comparison to effects in the Pacific Northwest.

Climate change also could have significant impacts on forest resources in the two regions. There is uncertainty in potential biological response to climate change, but in general, increased atmospheric CO_2 is expected to initially result in overall increases in forest productivity (McNulty and Aber 2001; Aber et al. 2001). As expected warming continues, there are increased likelihoods of drought-induced diebacks, changes in fire regimes, and susceptibility to insect damage and pathogen outbreaks (McNulty and Aber 2001; Aber et al. 2001), each of which could significantly reduce forest productivity. In terms of impacts on the southeastern US, Burton et al. (1997) note that the economic impacts of climate change on

southern forest producers are likely to generally be larger than national effects. McNulty et al. (1996) suggested the potential for severe ecosystem disruption and very strong long-term declines in net primary production (NPP) for many southern US pine forests. In the western US, wildfire is predicted to increase in frequency in response to climate change, due largely to increased fuel loads and increased likelihood of long-term drought (Aber et al. 2001).

Ideally, regional land-use modelers would understand not only climate, economic, and policy change, but how these processes interact to affect land-use change. In order to successfully predict impacts of climate change on forest resources in the southeastern US and Pacific Northwest, a regional modeler would ideally access a global model of forest industry adaptations to climate change. Given the globalization of wood product industry, climate change impacts on Canadian forestry, for example, could have a tremendous impact on utilization of forest resources in other regions (McCarl et al. 2000).

While this section has focused primarily on global and national drivers of change, local forces also affect land use. The next section will focus on some of the local factors affecting land-use change and land-use patterns.

Representation of local land-use pattern: southeastern US and Pacific Northwest

An understanding of geographic setting, land-use histories, and the primary drivers of land-use change

provides the capability to properly represent and model future land-use patterns. Land-use change is generally a local event, with relatively small patches of contiguous land affected by complete land-cover conversion at any one time (Sohl et al. 2004). It is the interaction of local agents (e.g., land-owners, corporations, government) that drive change at the local parcel level and produce unique local landscape patterns, and it is the aggregation of local land-use change that ultimately results in regional patterns of change. Linking land managers or decision-makers to the parcels of land they control is critical for many land-use applications (Rindfuss et al. 2004), as land owners have significant differences in how they manage the landscape and how those management practices affect land-use pattern (Turner et al. 1996).

Figure 6 depicts mapped historical (1974–2000) clear-cutting in a 10 km USGS Land Cover Trends study sample block, located in the Cascade Mountains of the Pacific Northwest. Land ownership in the area is a mixture of publicly owned lands (primarily National Forest land) and lands in private ownership. Historical clear-cutting patterns in the sample block illustrate stark differences in both the rates and spatial pattern of cutting between ownership types, with more cutting and larger patch sizes for clear-cuts on private land. Clear-cutting on National Forest lands in much of the Pacific Northwest has historically been conducted with 10–20 ha cuts, dispersed widely over areas of older forest (Spies et al. 1994; Wallin et al.

1994). This pattern of cutting was established to mitigate hydrologic effects of logging, minimize effects on biodiversity, and promote natural forest regeneration (Wallin et al. 1994). However, Spies et al. (1994) note the primary objective on private land in the area is typically to maximize short-term financial return, resulting in dramatically different patterns of forest change.

Public ownership is a much different issue in the southeastern US, where there is relatively little public land (Fig. 7). Private Industrial forestry ownership versus private individual (non-industrial) ownership becomes the most relevant ownership factor in the region, as private land-owners are significantly altering the characteristics of future forest resources in the region, but with major differences between the two private ownership types (Trani 2002). Significant population increases in parts of the US South, resultant urban development, and changing private ownership patterns on forest land have resulted in significant fragmentation and parcelization of the landscape (Fig. 8). Wear et al. (1999) showed a linear relationship between population growth and commercial forestry decline in Virginia, with commercial forestry effectively disappearing once population density reaches a certain threshold, while Zhang et al. (2005) showed that parcelization and increased non-industrial private ownership in the US South also has resulted in less intensive timber management.

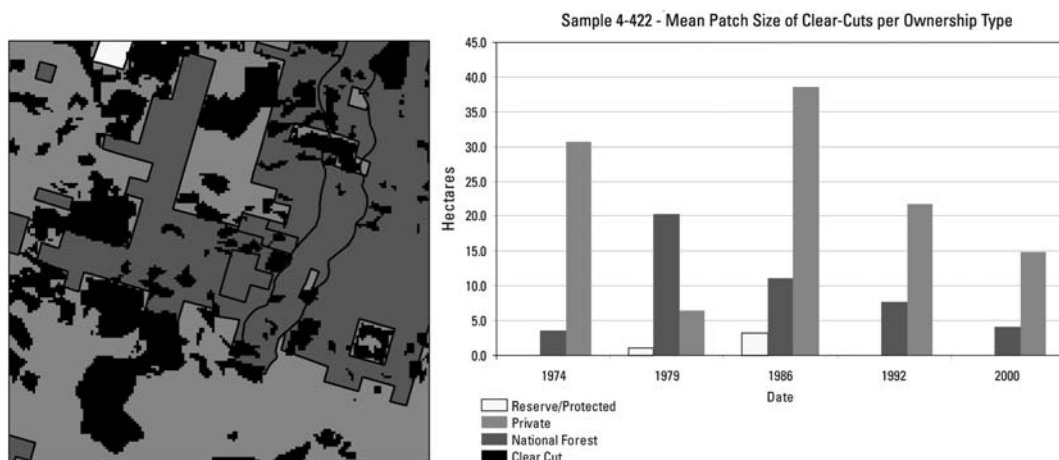


Fig. 6 USGS Land Cover Trends sample 4-422 from the Cascades ecoregion. Significant differences exist between private and public land in land management practices, with more cutting and larger patch sizes for clear-cuts on private land

Fig. 7 Federal and protected lands in the US. Significant portions of the Pacific Northwest are in public ownership, while the vast majority of the southeastern US is privately owned

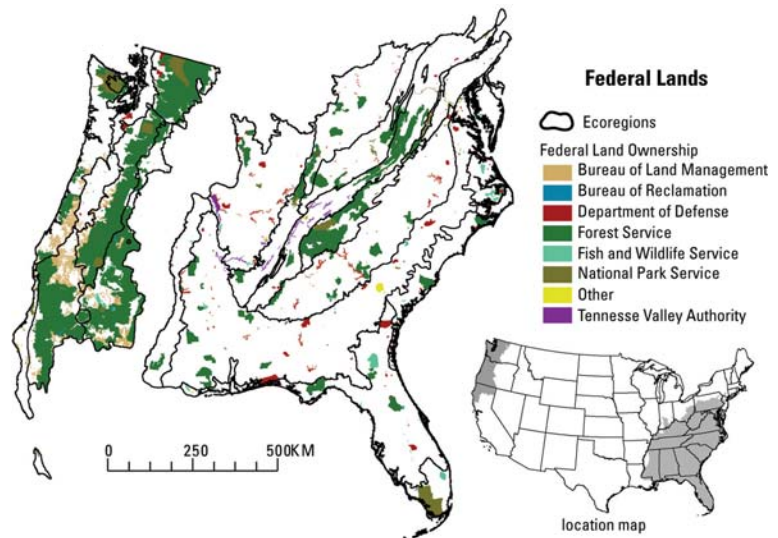
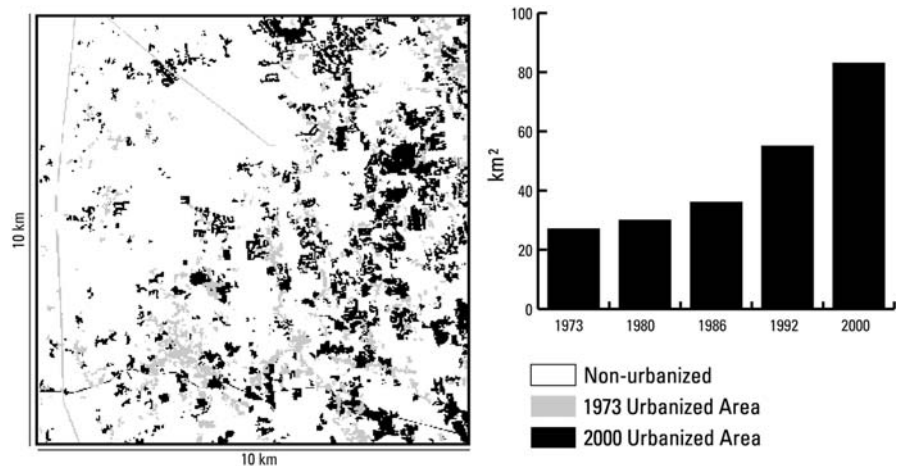


Fig. 8 USGS land cover trends sample in the Piedmont ecoregion in the southeastern US. Urbanization has had a very strong influence in the block, with urbanized area increasing from 27 to over 83 km² from 1973 to 2000



Shifts in ownership patterns in the southeastern US have the potential to dramatically alter forest structure in the region. However, spatially explicit data discriminating ownership type at the level of private industrial versus private non-industrial owner are not readily available on a regional basis, leaving a potential gap in establishing and modeling causality and resultant land-use change patterns in the southeastern US. This section has focused on ownership, but other forms of data useful for forecasting land-use pattern at the local level (e.g., local urban zoning and planning maps) are also often either difficult to obtain, or are difficult to consistently aggregate and utilize at regional scales.

Managing issues of scale and complexity: southeastern US and Pacific Northwest

Prior sections have shown the importance of drivers of change at global to local scales in the southeastern US and the Pacific Northwest. Climate change, effects of global economics and trade, and governmental policy all are likely to impact future forestry and other land-use change in the two areas, but will likely affect each region differently. At a local scale, land ownership is one of many local factors that will likely strongly affect both future land-use and land-use patterns in the two regions. It can be extremely difficult to represent all processes and feedbacks at

different scales. Agent-based modelers would argue that land-use modeling cannot operate successfully without attempts to model the human decision-making process (Parker et al. 2002), and that agent-based models offer the ability to link environmental and social processes (Matthews et al. 2007). Others would argue that representing behavior of individual agents and effects of their decisions on land use is difficult and often impractical (Verburg 2006), given that modelers must also model highly complex, dynamic spatial environments and processes, and feedbacks with human agents (Couclelis 2002).

Issues of scale are but one component of the inherent complexity of regional land-use modeling, as the processes affecting land-use change are interrelated and complex. Detailed, robust modeling of each variable affecting land use and modeling feedbacks between those variables is typically impossible to achieve. Regional land-use modelers must often use techniques to compartmentalize or generalize individual driving force effects. For example, at a regional scale, it is generally impractical to explicitly attempt to model the decision-making process for all individual entities (agents) in a study area. However, regional forecast models can still attempt to model the decision-making processes through generalization of individual decision-making entities into “bins” of similar entities. For the Cascades ecoregion example (Fig. 6), we can “bin” all private and public land-owners into distinct categories, and attempt to model a generalized decision-making process for groups of similar agents, and how their collective decisions are expressed as patterns of landscape change. If adequate ownership data were available, we could do the same for the southeastern US example, “binning” industrial private forest landowners and non-industrial private forest landowners, and modeling generalized decision-making processes for each. This level of generalization provides a level of representation of local decision-making processes, yet avoids the complexity of modeling individual land-owner decisions at a regional extent.

Similar levels of abstraction and generalization are often required for other drivers operating at global to local scales. It is impractical to explicitly and robustly model drivers of change operating at all relevant spatial and thematic scales. Modelers must contend with the inherent tradeoff between model

complexity and transparency, as decision-makers may be reluctant to consider land-use forecasts if the logic and processes can not be clearly and transparently communicated. Techniques for generalizing specific land-use processes offer the chance to simplify the land-use modeling process. Another opportunity to manage model complexity is the judicious use of well-developed scenarios, as discussed in the next section.

Need for scenario development: southeastern US and Pacific Northwest

The use of well-developed scenarios, with foundations developed by supporting land-use histories, offers the regional land-use modeler another opportunity to deal with model complexity, and also is vital for focusing the utility of land-use forecasts to address specific research questions. Scenarios can be used to assist the modeler in limiting variability in all the processes potentially affecting change. For example, attempting to account for all processes affecting land-use change in the southeastern US or Pacific Northwest would likely involve the integration and modeling of feedbacks between demographic projection models, econometric models, timber harvest models, global climate models, agent-based models of ownership changes, and many more. A more realistic approach is to develop scenarios with a set of a priori assumptions for certain potentially confounding driving force variables, reducing or eliminating the need to model those variables.

Modeling potential impacts of climate change on Pacific Northwest or southeastern US forestry, for example, could begin with the construction of multiple scenarios where assumptions are made regarding baseline economic or political conditions, variables that may be left constant between different model runs while climate variables are altered. Doing so reduces the need to examine feedback mechanisms between climate change and economic or political conditions, simplifies model construction, and allows for sensitivity analyses, testing how the landscape and systems governing it respond to select and focused changes in one or a few driving force variables (in this case, climate change). Such an approach is often very valuable to a policy-maker or land-manager, as it allows for the exploration of

potential outcomes from a specific policy or management choice.

The use of scenarios as a framework for analyzing regional land-use change may also help address issues of model uncertainty. Modeled estimates of future change are often extremely uncertain, but so are the inherent assumptions required to perform regional land-use modeling. Haynes (2003), for example, used an assumption of continuing 1999 US per capita wood consumption in projecting future forest change, but technological innovation or other unforeseen change could radically and unexpectedly change per capita wood consumption in the future. In addition, demographic projections required to calculate just how many “capita” will exist in the future are themselves wrought with uncertainty. Haynes (2003) also used the assumption that the US will have shrinking federal debts in future years and resultant lower long-term interest rates. The severe global recession beginning in 2008 brings into question the future validity of that assumption, an alteration of future reality severe enough to undoubtedly alter outlooks for the US timber industry. Despite these assumptions, however, the projections offered in the Haynes (2003) analysis still have high value, as the work was presented in a scenario framework which allows the exploration of one potential future, and allows decision makers to examine potential outcomes of their decisions under specific scenario conditions.

Discussion

For regional land-use modeling, there are several foundational elements which typically need to be addressed. This paper illustrates the effects of these foundational elements on potential land-use modeling in the southeastern US and the Pacific Northwest, and demonstrates the significant challenges modelers face in addressing those elements. While the case studies demonstrate difficulties in addressing each individual element, a primary overarching difficulty is the modeler’s ability to integrate social and biophysical processes from multiple disciplines, processes with inherently different spatial, temporal, and thematic foci, into one comprehensive model describing process and causality with respect to land-use change.

It must be realized that a perfect representation of all biophysical and socioeconomic processes affecting land-use change is impossible to achieve in a single model (Sohl and Sayler 2008; Verburg et al. 2008). However, we argue that regional land-use modelers should account for the foundational elements described in this paper. Although land-use models typically either assume a “top-down” or “bottom-up” hierarchy, both global- and national-level processes affecting regional change, as well as local-level processes, need to be incorporated in regional forecast models (Verburg 2006). Furthermore, modeling must account for how those multi-scale processes interact with each other within the context of scenarios describing future driving forces of change (Fig. 9). The case studies above illustrate the top-down influences of economics, climate, and policy variables, as well as the bottom-up influences of local-site variables (ownership). A successful approach for accounting for processes operating at different scales is to compartmentalize processes in distinct model modules. Models such as CLUE (Verburg and Veldkamp 2004; Verburg et al. 2008), for example, use a modular approach to account for processes operating at different scales, with global to national-scale processes (climate, economic, policy, etc.) driving a “demand” module, while site-specific local variables (ownership, etc.) drive a “spatial allocation” module.

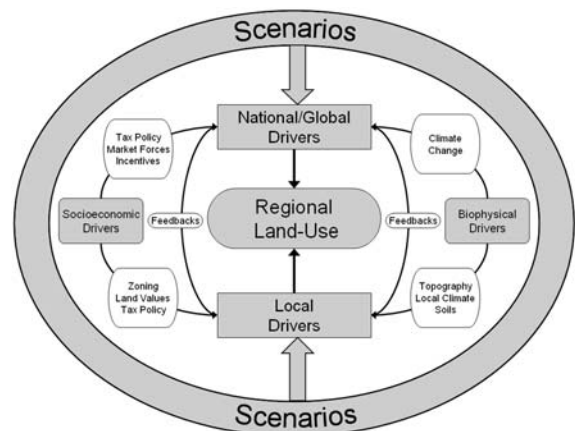


Fig. 9 Schematic diagram of integrated “top-down” and “bottom-up” approaches for regional land-use modeling. Depicted are relationships among the effects of national and global drivers of change, local drivers of change, and feedbacks between them, all in the context of scenarios designed to explore multiple possible futures

The case studies also illustrate the need for specific scenarios to focus research questions and limit model complexity. Tremendous uncertainty exists regarding future policy and its effects on land use, extent of climate impacts on both social and biophysical systems, and many other processes affecting land-use change in these two regions. A regional land-use forecast for the Pacific Northwest, were it conducted in the 1980s, could not possibly have foreseen the land-use effects of the Northwest Forest Plan or the 1990s Asian economic crisis. A regional land-use forecast for the southeastern US, were it conducted in the early 1980s, could not possibly have foreseen the land-use effects of a future CRP program or the 1990s US construction boom. Similarly, a contemporary land-use forecast study for the two regions would likely fail to see many major future economic or policy impacts on land use. The true power of regional forecast models is not to predict the future, attempting to defy this inherent uncertainty, but to explore alternative futures, allowing decision- and policy-makers the ability to envision potential outcomes of their decisions under specific scenarios. Scenarios define the overall regional modeling approach, identifying which processes and feedbacks are explicitly modeled, and which are defined by assumptions or fixed states.

Along with scenario development, another tool for dealing with model complexity is the use of existing models from other disciplines. Regional land-use models should take advantage of external research and modeling activities where possible. Verburg et al. (2008), for example, integrated a global economic model (global trade analysis project (GTAP); Hertel 1997) and an integrated assessment model (integrated model to assess the global environment (IMAGE); Strengers et al. 2004) with the CLUE-S land-use model. Sohl and Sayler (2008) advocated for integration of existing, robust forestry models such as PnET-II (Liang et al. 2002) with the FORE-SCE land-use model (Sohl et al. 2007; Sohl and Sayler 2008), using the robust but coarser scale forestry model to provide regional or county-level “demand” for a given forest usage, and then using FORE-SCE to spatially allocate that change at a finer scale. Modular land-use models facilitate integration of external models, allowing the land-use modeler to utilize specialized process models that are likely far more accurate and robust than could be developed by land-use modelers themselves.

It should also be understood that geographic variability of land-use change has significant implications for the transport of mapping and forecasting methodologies across regions (Sohl et al. 2004). We need to be cognizant of the difficulties in developing a “generalized”, transportable land-use model. Given the regional variability in drivers and characteristics of change and the spatial manifestation of that change, it is unlikely that one generalized model of land-use change could be developed and successfully applied regionally across the globe. However, modular approaches to land-use modeling allow for repeated uses of generalized process models regardless of geographic area being modeled. Modular approaches allow for a “plug-and-play” environment, where individual modules representing different processes may be used as needed.

Data availability remains a primary challenge for regional land-use forecast modeling. Land-use histories such as those provided by the USGS land cover trends study can play a vital role in regional land-use forecast modeling. Those data not only provide historical perspectives on rates and spatial patterns of landscape change, but can also be used to examine relationships among *place*, *process*, and *spatial pattern*. However, land-use histories such as these are often either not available or are lacking in quality and consistency (Kline and Alig 2001). Even where synoptic, consistent data sets are available from remotely-sensed sources, validity and quality issues sometimes affect modeling results. For example, Claggett et al. (2004) and Sohl et al. (2004) note the difficulties in using Landsat imagery to accurately detect and map low-density urbanization, a limitation that has a direct effect on the use of Landsat-based urbanization mapping to calibrate and train models such as SLEUTH (Claggett et al. 2004). Much of the low-density urbanization depicted in Fig. 8 is difficult to identify using Landsat alone, and likely would not have been correctly mapped without the manual interpretation methodologies used by the USGS trends study. The availability and validation of historical land-use data with a standardized set of “best practices” remains one of the foundations for land-use forecasting (Rindfuss et al. 2004).

Regional land-use forecast models have greatly evolved over the last 10 years, from what were often deterministic, empirically based models to robust, process-based models examining land-use change

processes operating at multiple relevant scales. The next 10 years will be marked by continued improvements in availability of spatially explicit land-use histories and driving force data that are vital to regional forecast models, as well as improvements in our ability to represent physical, biological, and cultural components affecting land-use change and the feedbacks between those components.

Acknowledgments Funding for this research was provided by the US Geological Survey's (USGS) Geographic Analysis and Monitoring Program with support from NASA's Land Cover and Land Use Change Program. Christopher Barnes' participation is supported through USGS contract 08HQC0005 with Stinger Ghaffarian Technologies (SGT) Inc.

References

- Aber J, Neilson RP, McNulty S et al (2001) Forest processes and global environmental change: predicting the effects of individual and multiple stressors. *Bioscience* 51:735–751
- Brown DG, Goovaerts P, Burnicki A et al (2002) Stochastic simulation of land-cover change using geostatistics and generalized additive models. *Photogramm Eng Rem S* 68:1051–1061
- Burton DM, McCarl BA, de Sousa CNM et al (1997) Economic impacts of climate change on southern forests. Texas A&M University, College Station
- Claggett PR, Jantz CA, Goetz SJ et al (2004) Assessing development pressure in the Chesapeake bay watershed: an evaluation of two land-use change models. *Environ Monit Assess* 94:129–146
- Conner RC, Hartsell AJ (2002) Forest area and conditions. In: Wear DN, Greis JG (eds) Southern forest resource assessment. General technical report SRS-53. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, pp 357–402
- Couclelis H (2002) Why I no longer work with agents: a challenge for ABMs of human-environment interactions. In: Parker DC, Berger T, Manson SM (eds) Agent-based models of land-use and land-cover change. Report and Review of an International Workshop, Irvine, 4–7 October 2001
- Daniels JM (2005) The rise and fall of the Pacific northwest log market. General technical report PNW-GTR-624. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland
- Gallant AL, Loveland TR, Sohl TL et al (2004) Using an ecoregion framework to analyze land-cover and land-use dynamics. *Environ Manage* 34:S89–S110
- Geoghegan J, Pritchard L Jr, Ogneva-Himmelberger Y et al (1998) "Socializing the pixel" and "pixelizing the social" in land-use and land-cover change. In: Liverman D, Moran EF, Rindfuss RR, Stern PC (eds) People and pixels. National Research Council, Washington, DC, pp 51–69
- Haynes RW (2003) An analysis of the timber situation in the United States:1952 to 2050. General technical report PNW-GTR-560. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland
- Hertel TW (1997) Global trade analysis: modelling and applications. Cambridge University Press, Cambridge
- Irwin EG, Geoghegan J (2001) Theory, data, methods: developing spatially explicit economic models of land use change. *Agric Ecosyst Environ* 85:7–24
- Kline JD, Alig RJ (2001) A spatial model of land use change for western Oregon and western Washington. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland. Research Paper PNW-RP-528
- Lane CL (1998) Log export and import restrictions of the U.S. Pacific northwest and British Columbia: past and present. General technical report PNW-GTR-436. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland
- Liang Y, Durrans SR, Lightsey T (2002) A revised version of PnET-II to simulate the hydrologic cycle in southeastern forested areas. *J Am Water Resour Assess* 38:79–89
- Loveland TR, Sohl TL, Stehman SV et al (2002) A strategy for estimating the rates of recent United States land-cover changes. *Photogramm Eng Rem S* 68:1091–1099
- Loveland TR, Gutman G, Buford M et al (2003) Chapter 6: land use/land cover change. In: Strategic plan for the climate change science program. U.S. Climate Change Science Program, Washington, pp 118–134
- Marcucci DJ (2000) Landscape history as a planning tool. *Landsc Urban Plan* 49:67–81
- Matthews R, Gilbert N, Roach A et al (2007) Agent-based land-use models: a review of applications. *Landscape Ecol* 22:1447–1459
- McCarl BA, Adams DM, Alig RJ et al (2000) Effects of global climate change on the U.S. forest sector: response functions derived from a dynamic resource and market simulator. *Clim Res* 15:195–205
- McNulty SG, Aber JD (2001) U.S. national climate change assessment on forest ecosystems: an introduction. *Bio-Science* 51:720–722
- McNulty SG, Vose JM, Swank WT (1996) Potential climate change effects on loblolly pine forest productivity and drainage across the southern United States. *Ambio* 25:449–453
- Naveh Z (2001) Ten major premises for a holistic conception of multifunctional landscapes. *Landsc Urban Plan* 57:269–284
- Omerik JM (1987) Ecoregions of the conterminous United States. *Ann Assoc Am Geogr* 77:118–125
- Parker DC, Berger T, Manson SM (eds) (2002) Agent-based models of land-use and land-cover change. Report and review of an international workshop, Irvine
- Parker DC, Manson SM, Janssen MA et al (2004) Multi-agent systems for the simulation of land-use and land-cover change: a review. *Ann Assoc Am Geogr* 93:314–337
- Pontius RG, Spencer J (2005) Uncertainty in extrapolations of predictive land-change models. *Environ Plan B Plan Des* 32:211–230
- Pontius RG, Boersma W, Castella J, Clarke K, de Nijs T, Dietzel C, Duan Z, Fotsing E, Goldstein N, Kok K,

- Koomen E, Lippitt CD, McConnell W, Sood AM, Pijanowski B, Pithadia S, Sweeney S, Trung TN, Veldkamp AT, Verburg PH (2008) Comparing the input, output, and validation maps for several models of land change. *Ann Reg Sci* 42:11–37
- Poudevigne I, Baudry J (2003) The implication of past and present landscape patterns for biodiversity research: introduction and overview. *Landscape Ecol* 18:223–225
- Rindfuss RR, Walsh SJ, Turner BL II et al (2004) Developing a science of land change: challenges and methodological issues. *Proc Natl Acad Sci* 101:976–981
- Sohl TL, Saylor KL (2008) Using the FORE-SCE model to project land-cover change in the southeastern United States. *Ecol Model* 219:49–65
- Sohl TL, Gallant AL, Loveland TR (2004) The characteristics and interpretability of land surface change and implications for project design. *Photogramm Eng Rem S* 70: 439–448
- Sohl TL, Saylor KL, Drummond MA et al (2007) The FORE-SCE model: a practical approach for projecting land use change using scenario-based modeling. *J Land Use Sci* 2:102–126
- Spies TA, Ripple WJ, Bradshaw GA (1994) Dynamics and pattern of a managed coniferous forest landscape in Oregon. *Ecol Appl* 4:555–568
- Strengers B, Leemans R, Eickhout B et al (2004) The land-use projections and resulting emissions in the IPCC SRES scenarios as simulated by the IMAGE 2.2 model. *GeoJ* 61:381–393
- Tomlin CD (1990) *Geographic information systems and cartographic modeling*. Prentice Hall, New Jersey
- Trani MK (2002) *Terrestrial ecosystems*. In: Wear DN, Greis JG (eds) *Southern forest resource assessment*. General technical report SRS-53. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville
- Turner MG, Wear DN, Flamm RO (1996) Land ownership and land-cover change in the southern Appalachian Highlands and the Olympic Peninsula. *Ecol Appl* 6:1150–1172
- Verburg PH (2006) Simulating feedbacks in land use and land cover change models. *Landscape Ecol* 21:1171–1183
- Verburg PH, Veldkamp A (2004) Projecting land use transitions at forest fringes in the Philippines at two spatial scales. *Landscape Ecol* 19:77–98
- Verburg PH, Schot P, Dijst M et al (2004) Land use change modeling: current practice and research priorities. *GeoJ* 61:309–324
- Verburg PH, Eickhout B, van Meijl H (2008) A multi-scale, multi-model approach for analyzing the future dynamics of European land use. *Ann Reg Sci* 42:57–77
- Wallin DO, Swanson FJ, Marks B (1994) Landscape pattern response to changes in pattern generation rules: land-use legacies in forestry. *Ecol Appl* 4:569–580
- Wear DN, Greis JG (eds) (2002) *Southern forest resource assessment*. General technical report SRS-53. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville
- Wear DN, Liu R, Foreman JM et al (1999) The effects of population growth on timber management and inventories in Virginia. *For Ecol Manag* 118:107–115
- Wimberly MC, Ohmann JL (2004) A multi-scale assessment of human and environmental constraints on forest land cover change on the Oregon (USA) coast range. *Landscape Ecol* 19:631–646
- Wu X, Hu Y, He HS et al (2008) Performance evaluation of the SLEUTH model in the Shenyang metropolitan area of northeastern China. *Environ Model Assess* 13:1–10
- Zampella RA, Procopio NA, Lathrop RG et al (2007) Relationship of land-use/land-cover patterns and surface-water quality in the Mullica river basin. *J Am Water Resour Assess* 43:594–604
- Zhang Y, Zhang D, Schelhas J (2005) Small-scale non-industrial private forest ownership in the United States: rationale and implications for forest management. *Silva Fenn* 39:443–454